



**Rolf Follath**  
**for the BESSY optic group**

**Beamlines for the BESSY - FELs**

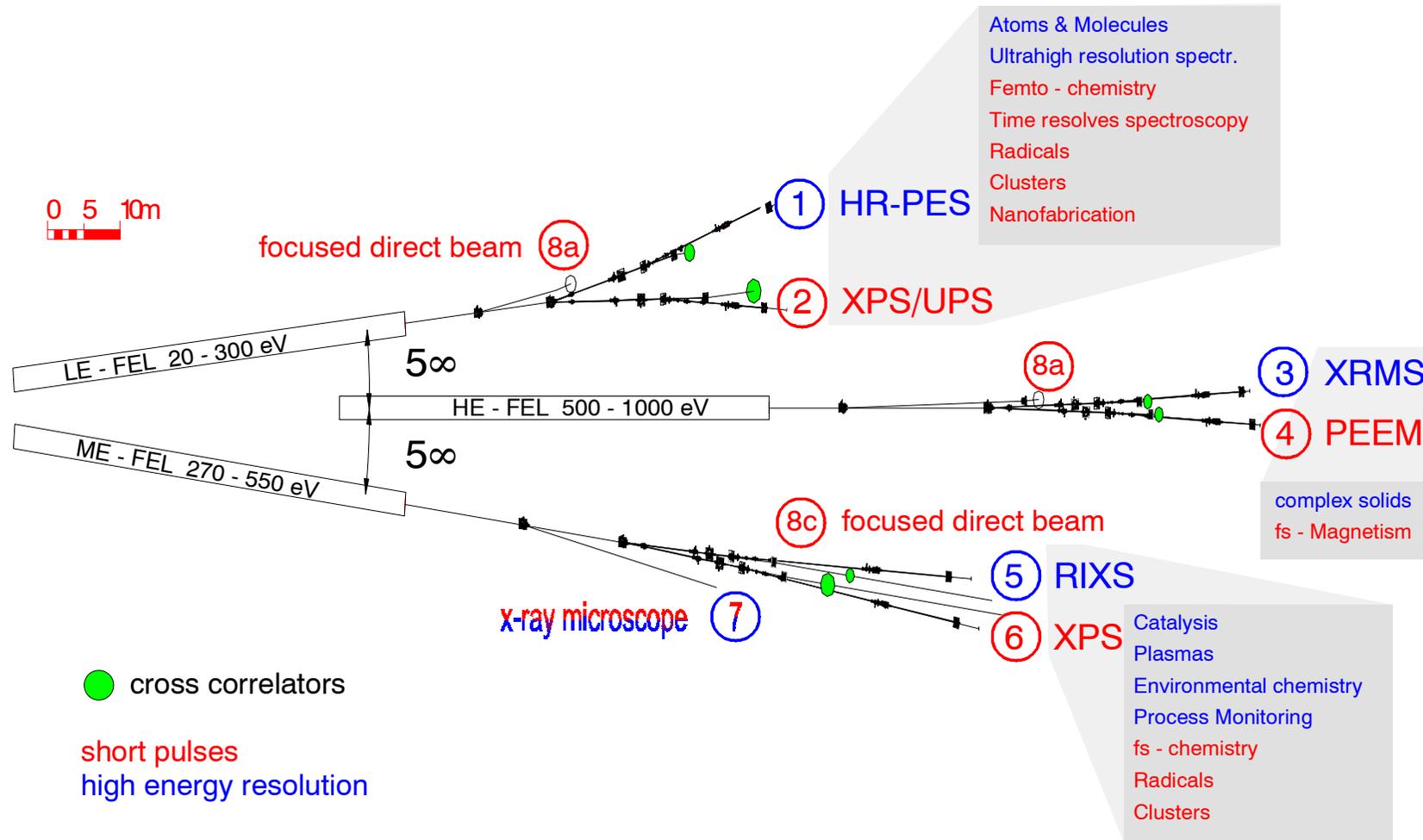
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**Modified plane grating monochromators**

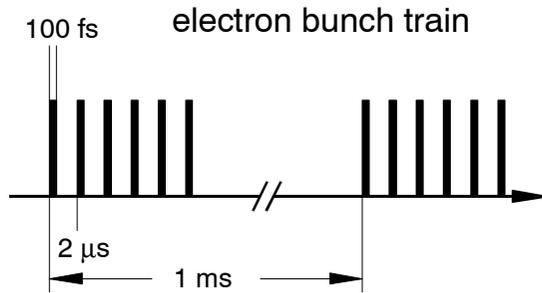
			<b>photon energy</b>	<b>Coating</b>
low energy	high res. short pulses	(LEFEL)	20 - 265 eV 20 - 300 eV	Carbon Si
intermediate energy range		(MEFEL)	270 - 550 eV	Au / Si / Ni
high energy range		(HEFEL)	500 - 1000 eV	Carbon / SiC

# Beamlines for the BESSY - FELs

experiments



normal conducting injector  
1 nC  
6 pulses per macropulse  
1000 macropulses / s



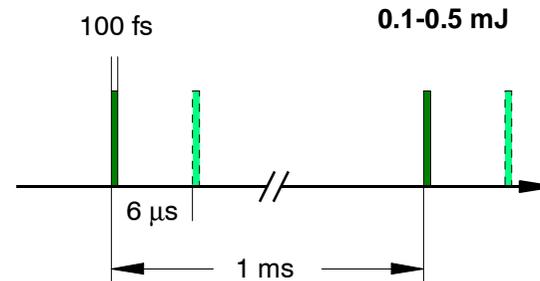
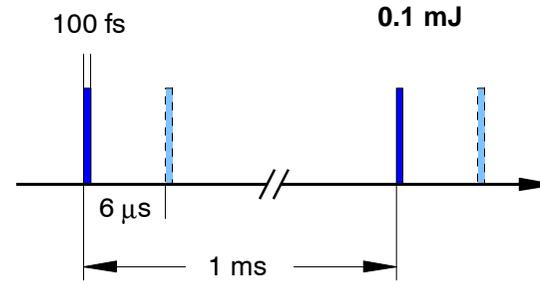
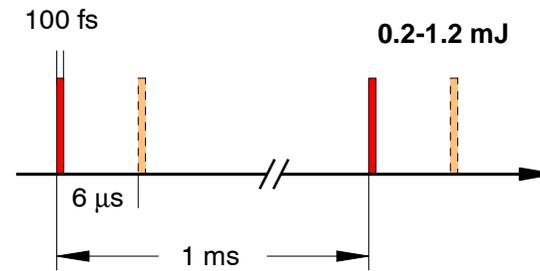
(super-conducting injector)  
1 nC  
25 kHz per FEL

LE-FEL 20 - 300 eV

HE-FEL 500 - 1000 eV

ME-FEL 270 - 550 eV

photon bunch trains



<b>source parameters</b>		U41	LE-FEL	ME-FEL	HE-FEL
photon energy		160 eV	20 eV	270 eV	1000 eV
		I=100 mA	f=25 kHz	f=25 kHz	f=25 kHz
		k=2.5	1.2 mJ	0.45 mJ	0.11 mJ
<b>photon beam parameters</b>					
angular flux density	[W/mrad <sup>2</sup> ]	420	440	6100	6200
avg. photon number	[1/s]	4·10 <sup>15</sup>	1·10 <sup>19</sup>	2.5·10 <sup>17</sup>	2·10 <sup>16</sup>
photons per pulse		1.3·10 <sup>7</sup>	4·10 <sup>14</sup>	1·10 <sup>13</sup>	7·10 <sup>11</sup>
bandwidth	(FWHM) [eV]	4.6	0.2	0.6	1
pulse length	(FWHM) [ps]	50	0.1	0.1	0.1
mirror position	[m]	17	20	30	30
flux density	[W/mm <sup>2</sup> ]	1.4	1.1	8	8
beam width	(FWHM) [mm]	2	5	1.2	0.7
total power	[W]	14	30	11	3
photon density	[1/nm <sup>2</sup> /pulse]	4·10 <sup>-6</sup>	20	9	2

### Properties of FEL beam:

- high angular flux density
- high (temporal) peak photon flux
- low average power
- short pulses

### Questions

- damage of optical surfaces
  - ~ ionisation (?? eV / atom)
  - ~ ablation (50 mJ / cm<sup>2</sup>)
  - ~ thermal deformation
- pulse broadening

20 eV, 200 l/mm c=2, plane mirror

### transient heat load calculation (Mechanica)

#### pulse parameters:

incident angle	$7^\circ$
penetration depth (1/e)	5 nm
absorbed power density	6.25 MW/mm <sup>2</sup>
pulse length	100 fs
power load	0.2 W
deposited energy	20 fJ

#### material parameters:

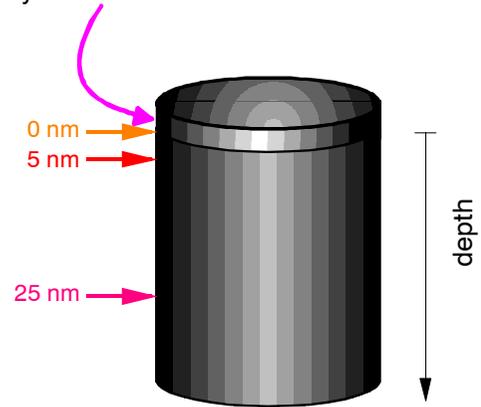
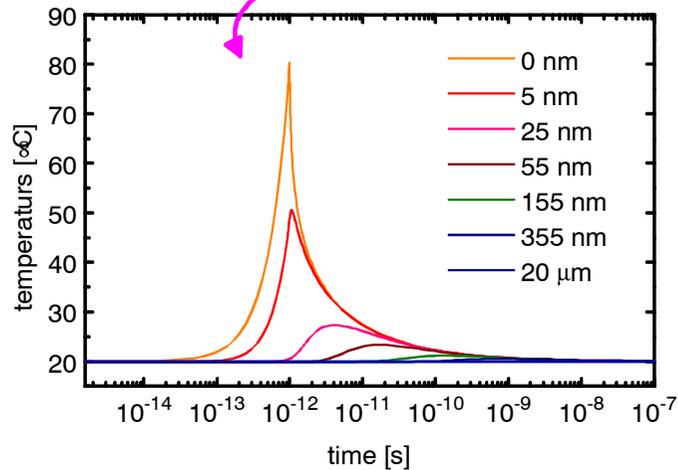
material	silicon
diameter	200 nm
length	20 $\mu$ m

### coarse estimation

pulse energy  $\Delta Q$  is absorbed  
within penetration depth  $t_e = 5$  nm

$$\Delta T = \Delta Q / (c_p m) = 77 \text{ K}$$

conversion from laser pulse to heat within 1 ps in layer of 5 nm thickness



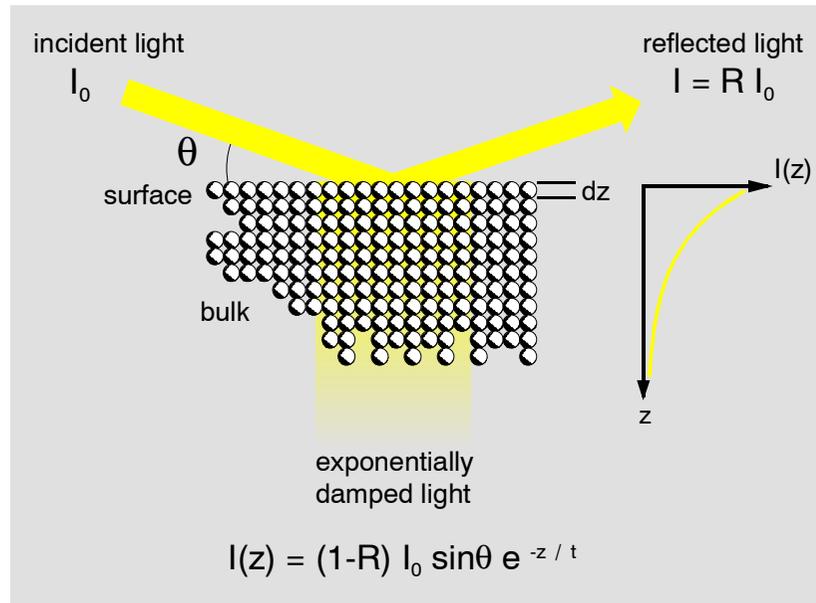
pulse energy is thermalized within some ns

no damage of surface

# Beamlines for the BESSY - FELs

## total external reflection

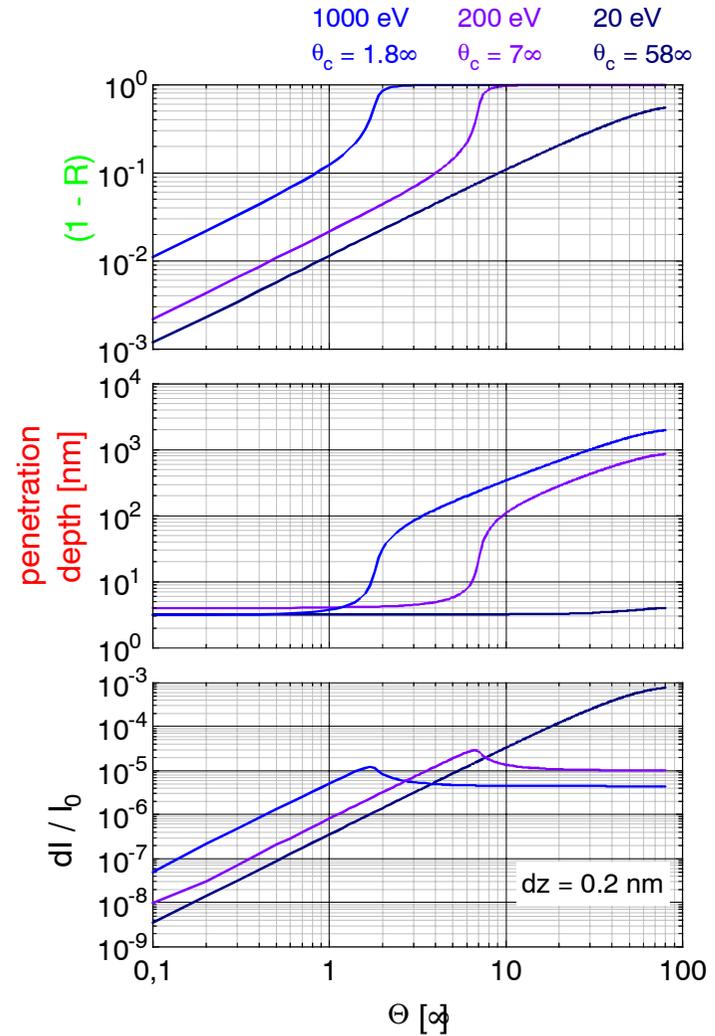
carbon



absorbed by first layer  $dz$

$$\frac{dI}{I_0} = \frac{(1-R) \sin\theta}{t} dz$$

layer thickness  $dz = 0.2..0.3 \text{ nm}$   
 penetration depth  $t = 1..5 \text{ nm}$

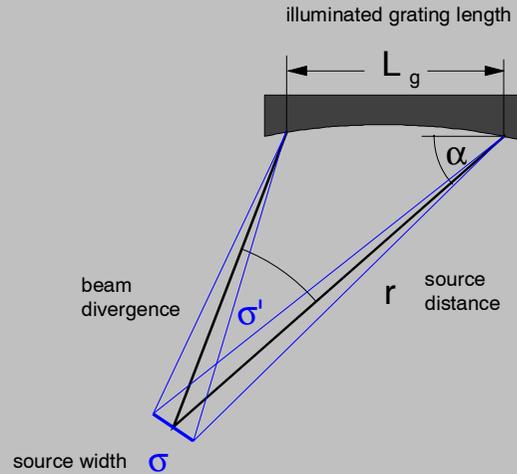


grating illuminated by beam with source size  $\sigma$  and divergence  $\sigma'$

source limited resolution

$$N k \lambda = \cos \alpha - \cos \beta$$

$$\Delta \lambda = \frac{\sin \alpha}{N k} \cdot \frac{\sigma}{r}$$



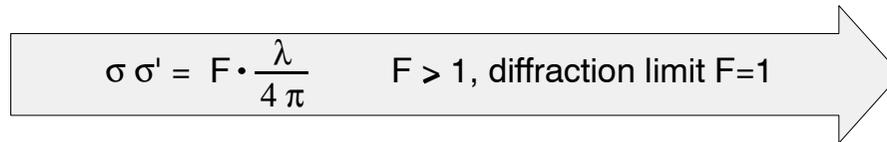
pulse broadening

$$L_g = \frac{r \sigma'}{\cos \alpha}$$

every illuminated line prolongs pulse by on wavelength

$$\Delta T = \frac{L_g N k \lambda}{c} = \frac{N k r \lambda}{c \sin \alpha} \sigma'$$

$$\Delta \lambda \cdot \Delta T = \frac{\sigma \sigma' \lambda}{c}$$



$$\Delta E \cdot \Delta T = F \cdot \frac{h}{4 \pi}$$

pulse length is transform limited if beam is diffraction limited.  
 F as low as possible => diffraction limited beams.

A. Meseck, Genesis calculations:

$\sigma$  - values

energy	size $\sigma$	divergence $\sigma'$	gaussian div. $\sigma'=\lambda / (4\pi\sigma)$	F	pulse length	pulse energy	BW	photons per pulse	
LEFEL	20 eV	310 $\mu\text{m}$	110 $\mu\text{rad}$	16 $\mu\text{rad}$	7	50 fs	1.2 mJ	70 meV	$4 \cdot 10^{14}$
	300 eV	105 $\mu\text{m}$	13 $\mu\text{rad}$	3 $\mu\text{rad}$	4	40 fs	0.2 mJ	110 meV	$4 \cdot 10^{12}$
MEFEL	270 eV	65 $\mu\text{m}$	18 $\mu\text{rad}$	6 $\mu\text{rad}$	3	40 fs	0.5 mJ	240 meV	$1 \cdot 10^{13}$
	550 eV	95 $\mu\text{m}$	12 $\mu\text{rad}$	2 $\mu\text{rad}$	6	40 fs	0.1 mJ	350 meV	$1 \cdot 10^{12}$
HEFEL	500 eV	110 $\mu\text{m}$	15 $\mu\text{rad}$	2 $\mu\text{rad}$	8	40 fs	0.1 mJ	250 meV	$1 \cdot 10^{12}$
	1000 eV	80 $\mu\text{m}$	9 $\mu\text{rad}$	1 $\mu\text{rad}$	9	50 fs	0.1 mJ	400 meV	$7 \cdot 10^{11}$

- accept complete beam, no clipping
- total external reflections
- energy density significantly lower than ablation threshold (50 mJ / cm<sup>2</sup>)

- high energy resolution : full illumination of grating  
(example for highest photon energies)
- short pulses : least possible illuminated grating lines  
(example for lowest photon energies)

accomplished within one beamline by

brute force : baffling the grating

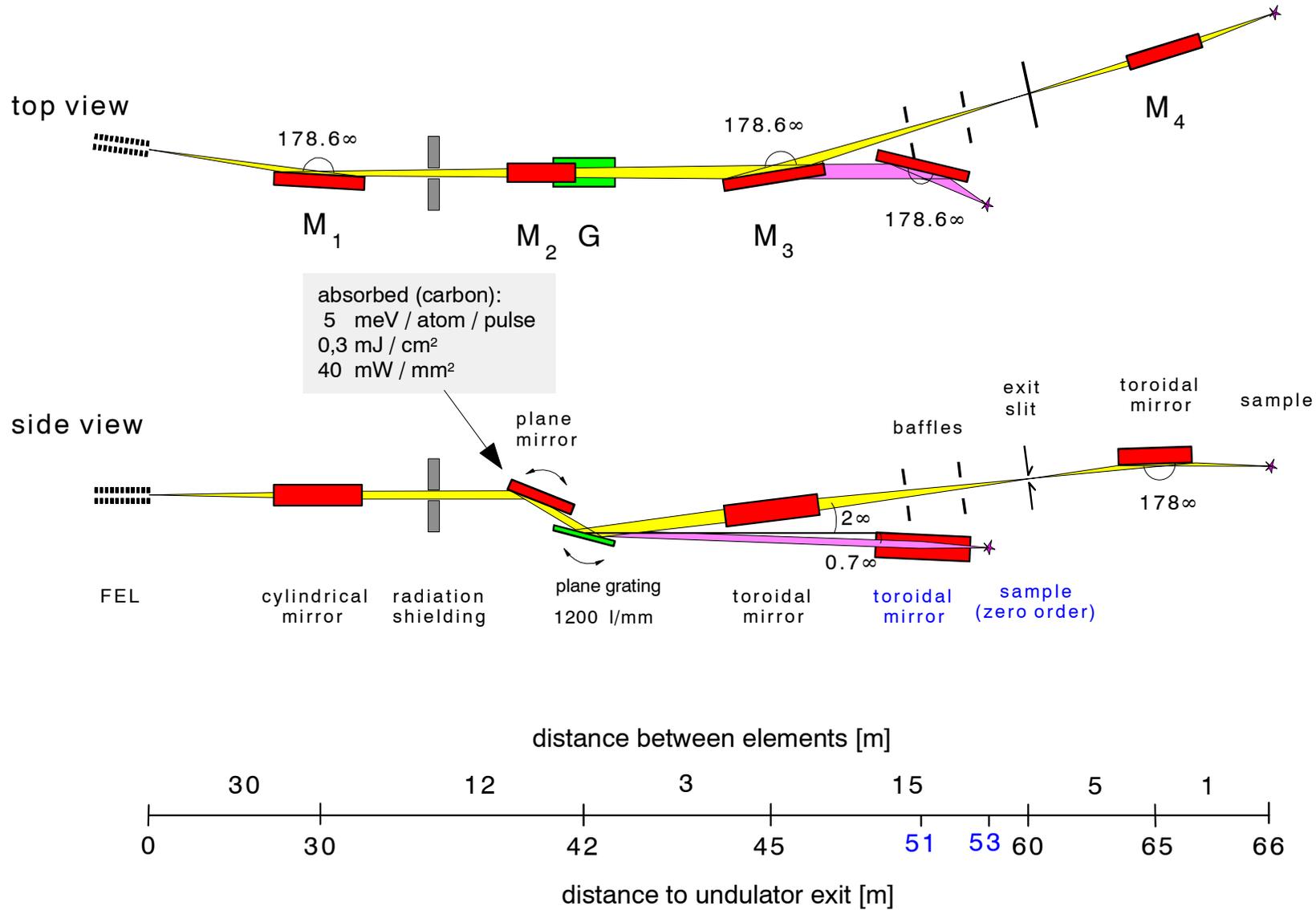
intelligent : varying incident angle on grating (within tot. ext. refl.)  
(varying beam cross section by preoptics)

# High energy beamline

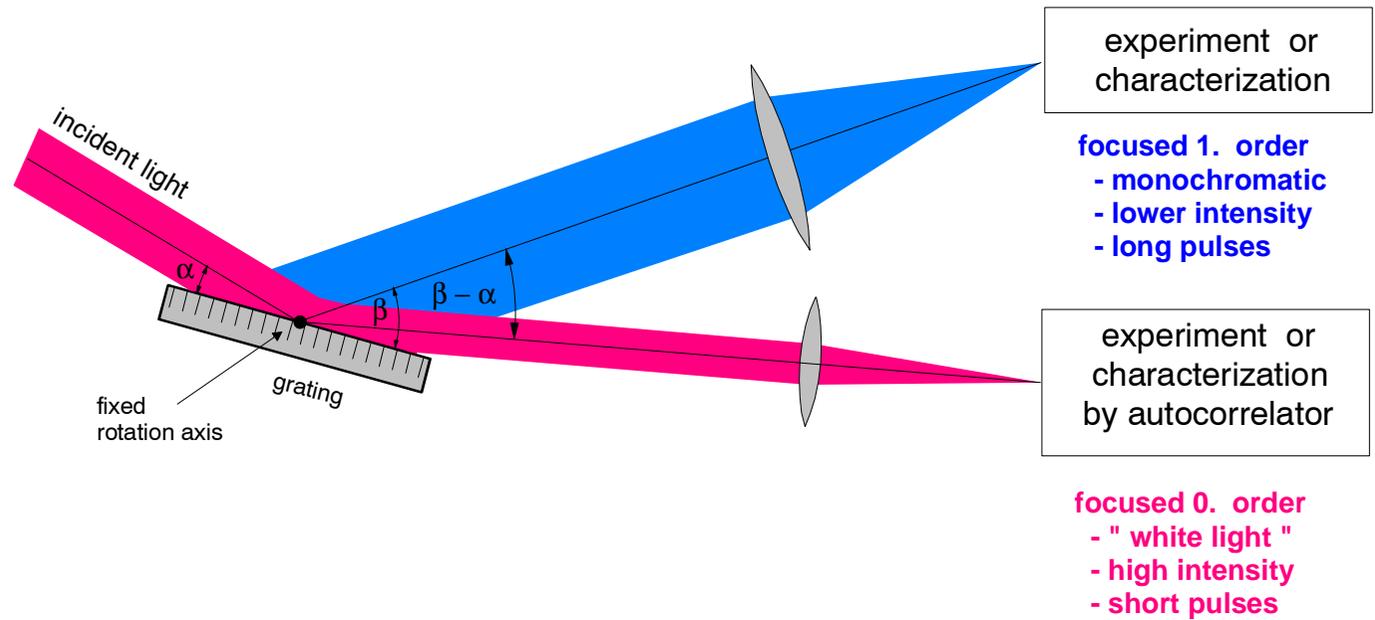
optical design

PGM in collimated light

500 - 1000 eV



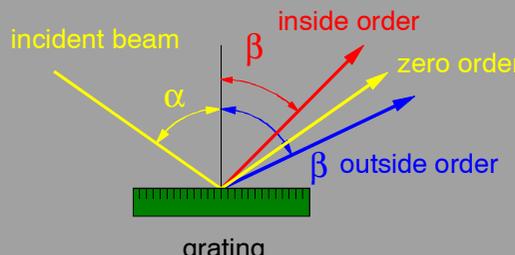
on blaze condition => fixed beams in space, grating acts as 'beam-splitter'



- energy resolved experiments in 1. order
- correlator in 0. order

<=>

- timing experiments in 0. order
- post mortem energy-determination in 1. order



Incident beam

inside order

zero order

outside order

grating

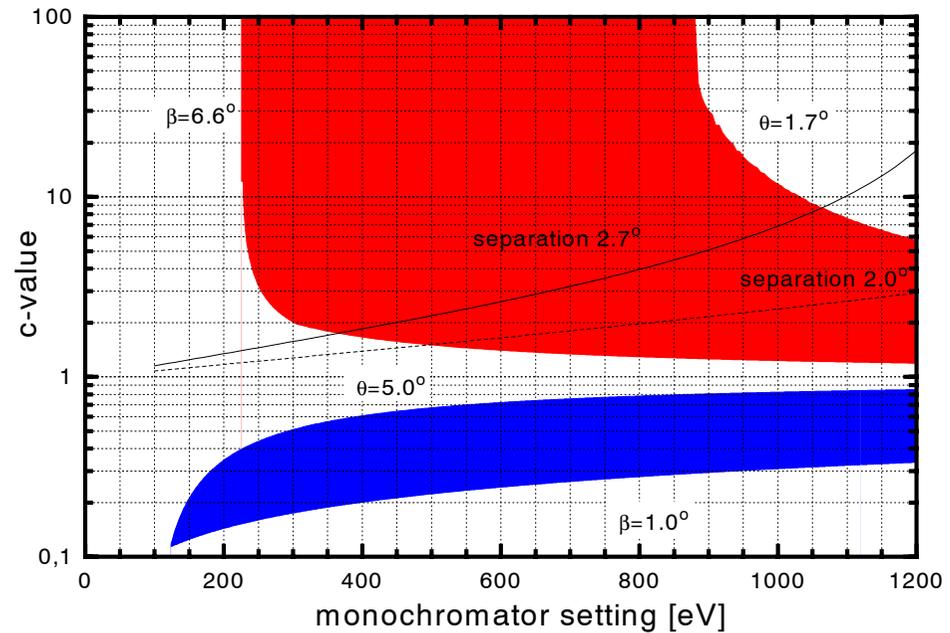
grating equation:

$$N k \lambda = \sin \alpha + \sin \beta$$

definition of c-value:

$$c = \frac{\cos \beta}{\cos \alpha}$$

$\lambda$  : wavelength  
 $N$  : line density  
 $k$  : diffraction order  
 $\alpha, \beta$  : angle of incidence and diffraction  
 $2\theta$  : deviation angle ( $2\theta = \alpha - \beta$ )



limits :

$$\theta = [1.7^\circ; 5.0^\circ]$$

$$\beta = [1.0^\circ; 6.6^\circ]$$

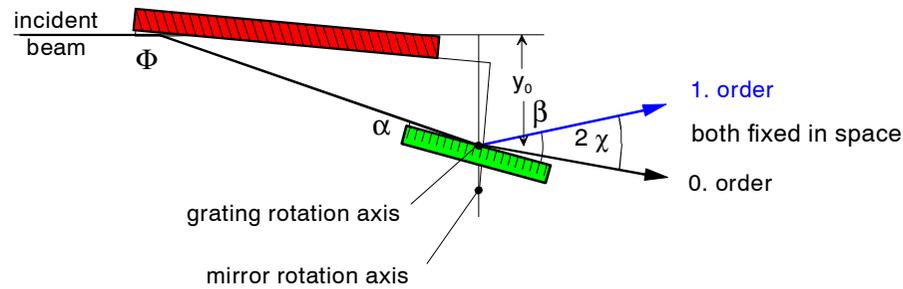
Inside diffraction order

Outside diffraction order

Fixed angular separation

reflectivity on plane mirror

## plane mirror / plane grating mechanic (SX 700 mounting)

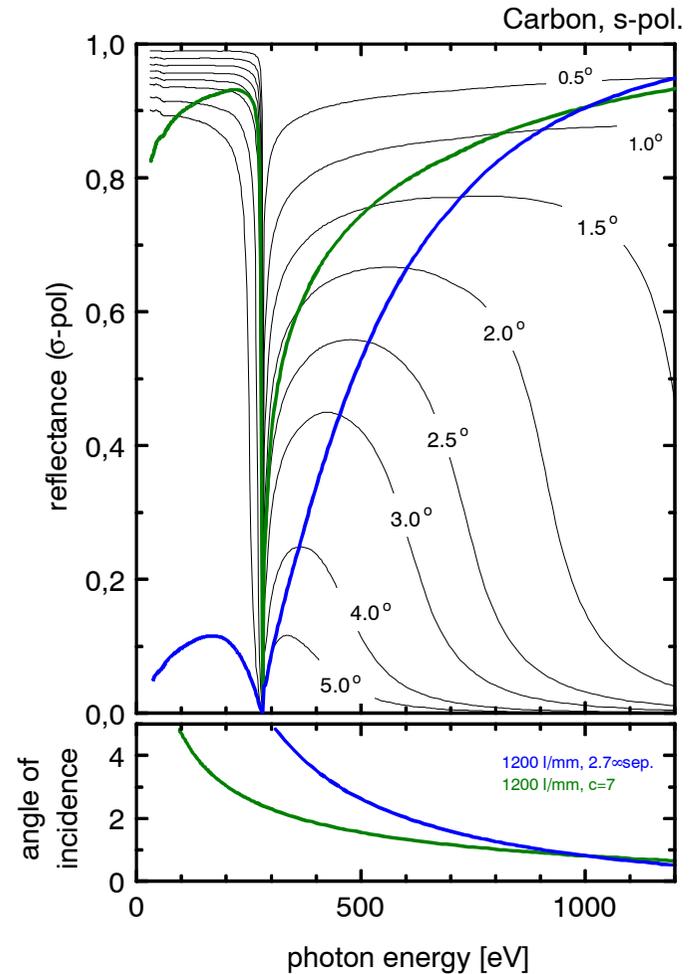


Mode 1: Maintaining the on blaze condition at the grating keeps 1. order and 0. order beams fixed in space.

$$2\chi = \beta - \alpha$$

Mode 2: High energy resolution mode,  $c = 7$

in both modes, working curve for fixed c-value stays in the total external reflection regime ( $\phi = \theta - 2^\circ$ ).



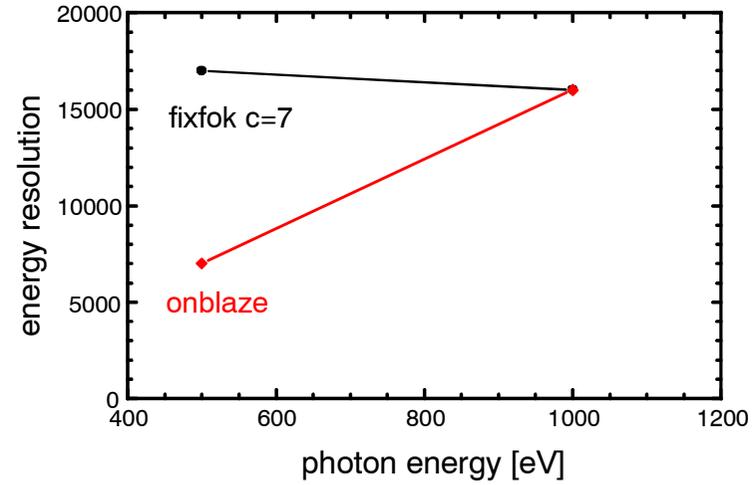
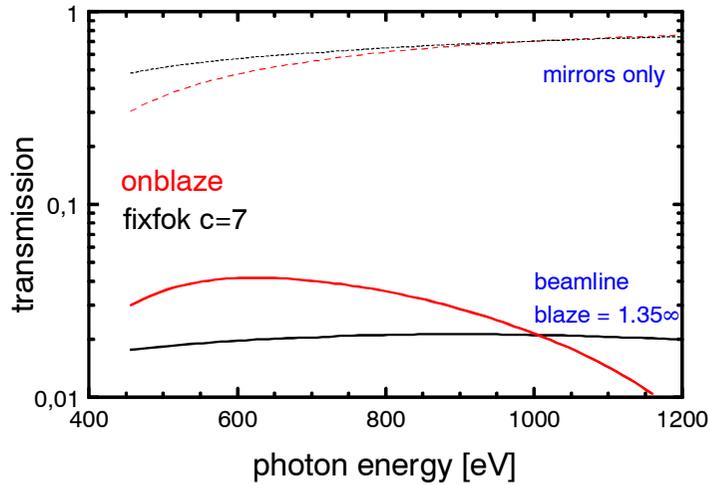
reflectance for fixed incident angles  
 working curve of plane mirror for fixed separation of 2.7 μm  
 working curve of plane mirror for c = 7 (high resolution).

# High energy beamline

performance

1200 l/mm, c=7 / onblaze

horizontal polarization



- carbon coating on all elements
- 500 - 1000 eV
- 1.35∞blaze angle
- approx. 2% - 4% transmission

photon energy	[eV]	500	1000
slit size	[mm]	7.5 / 10	7.5
bandwidth	[meV]	30 / 70	60
pulse length	[mm]	280 / 66 / 33	120
	[fs]	900 / 210 / 100	400
spot size	[μm <sup>2</sup> ]	45 x 80	35 x 35

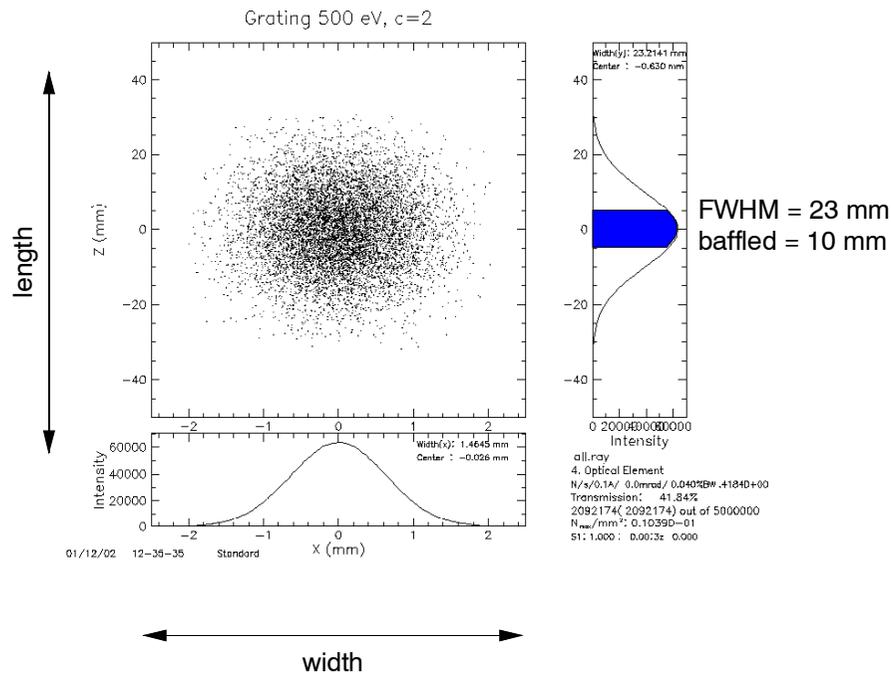
energy resolution at 500 eV, c=7 balances source size / slope errors / abberations

# High energy beamline

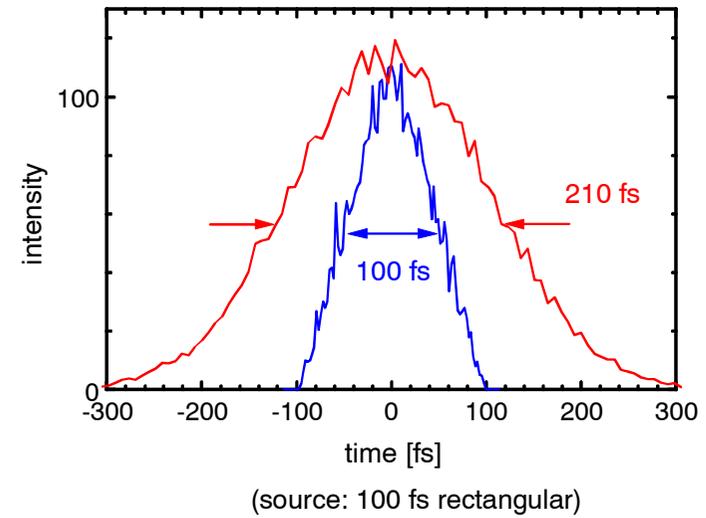
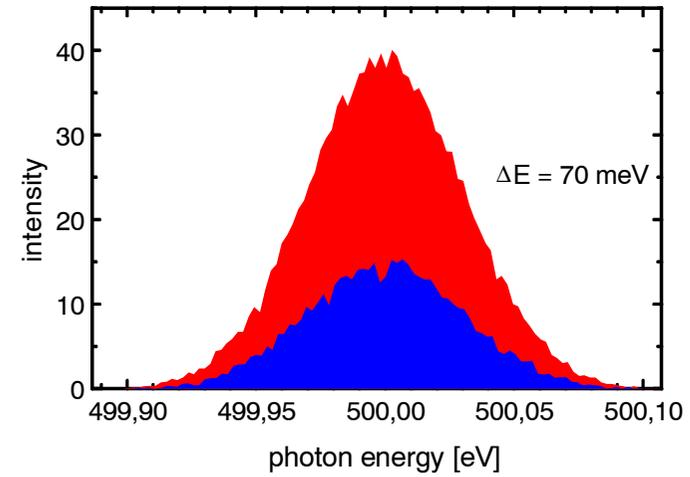
# controlling the pulse broadening

baffling at 500 eV, 1200 l/mm  $c=2$ , 10  $\mu\text{m}$  slit

## grating illumination



confining illuminated grating length  
=> pulse length unchanged



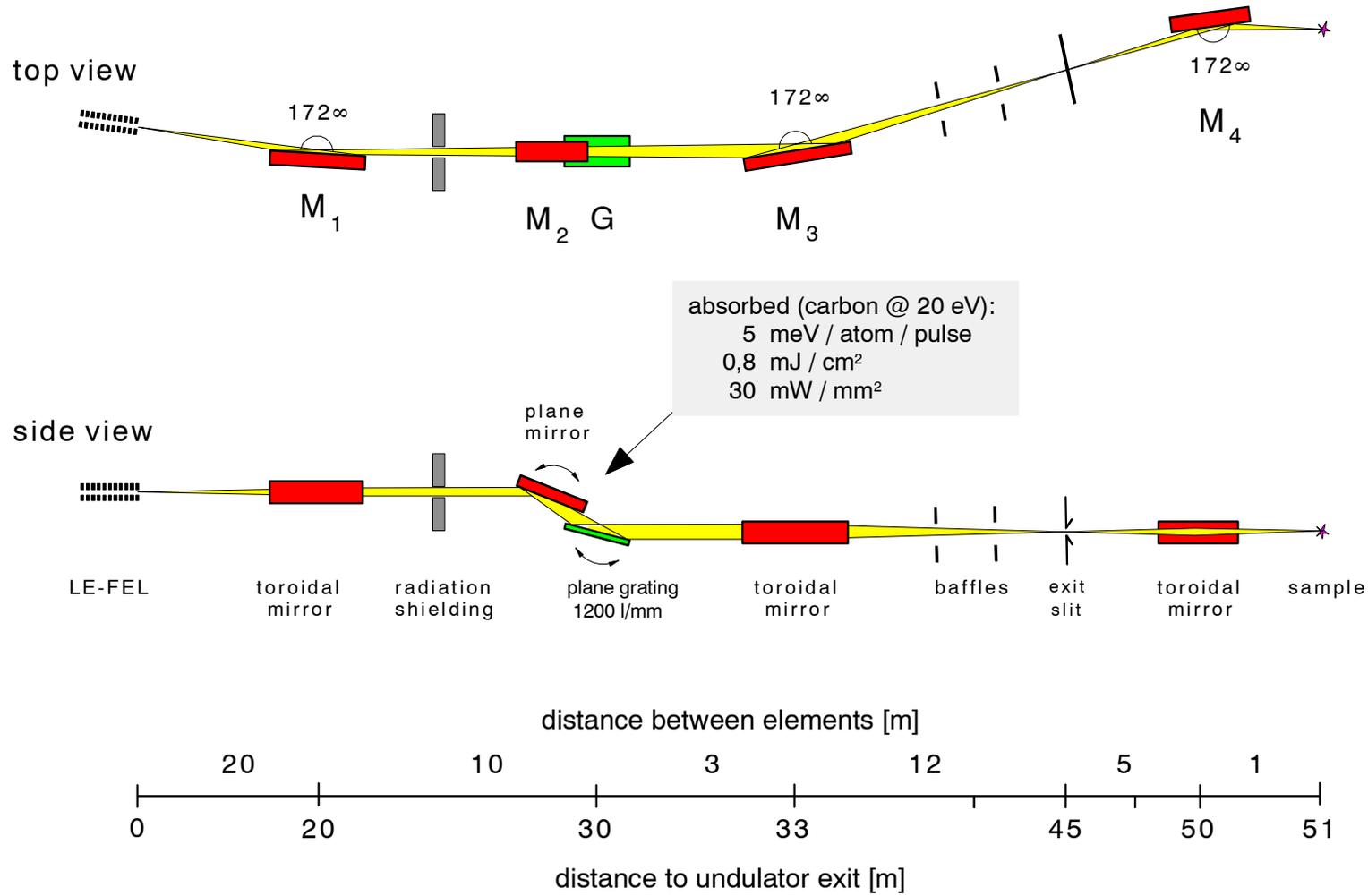
# Low energy beamline

# optical design

PGM in collimated light

optimized  $c=7.5$

20 - 250 eV

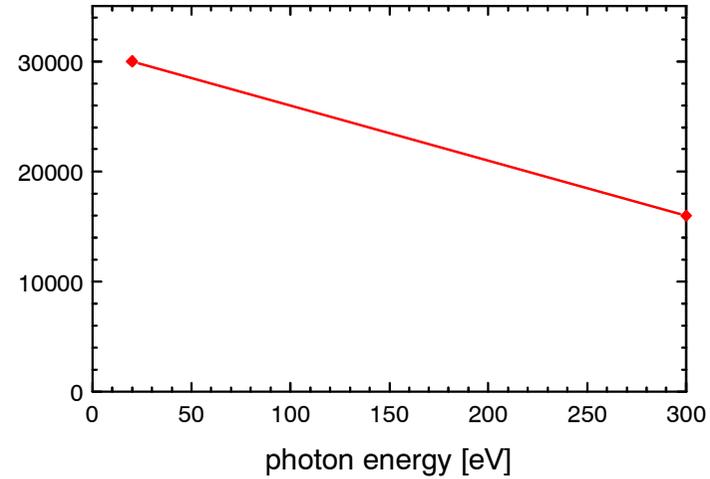
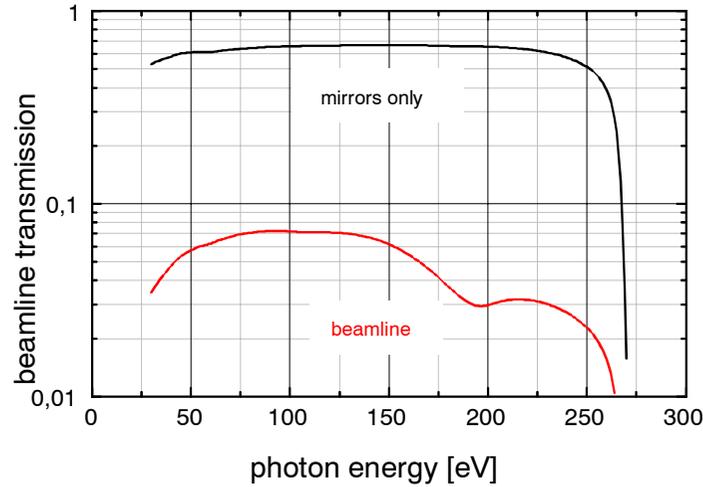


# Low energy beamline

performance

1200 l/mm, c=7.5, 30 μm slit

horizontal polarization



- carbon coating on all elements
- 20 - 260 eV
- 3° blaze angle
- approx. 5% transmission
- no absorption edges
- on blaze mode requires very large angular motions

photon energy	[eV]	20	300
bandwidth	[meV]	0.65	19
pulse length	[mm]	7	0.23
	[ps]	23	0.76
spot size	[μm <sup>2</sup> ]	500 x 80	50 x 6

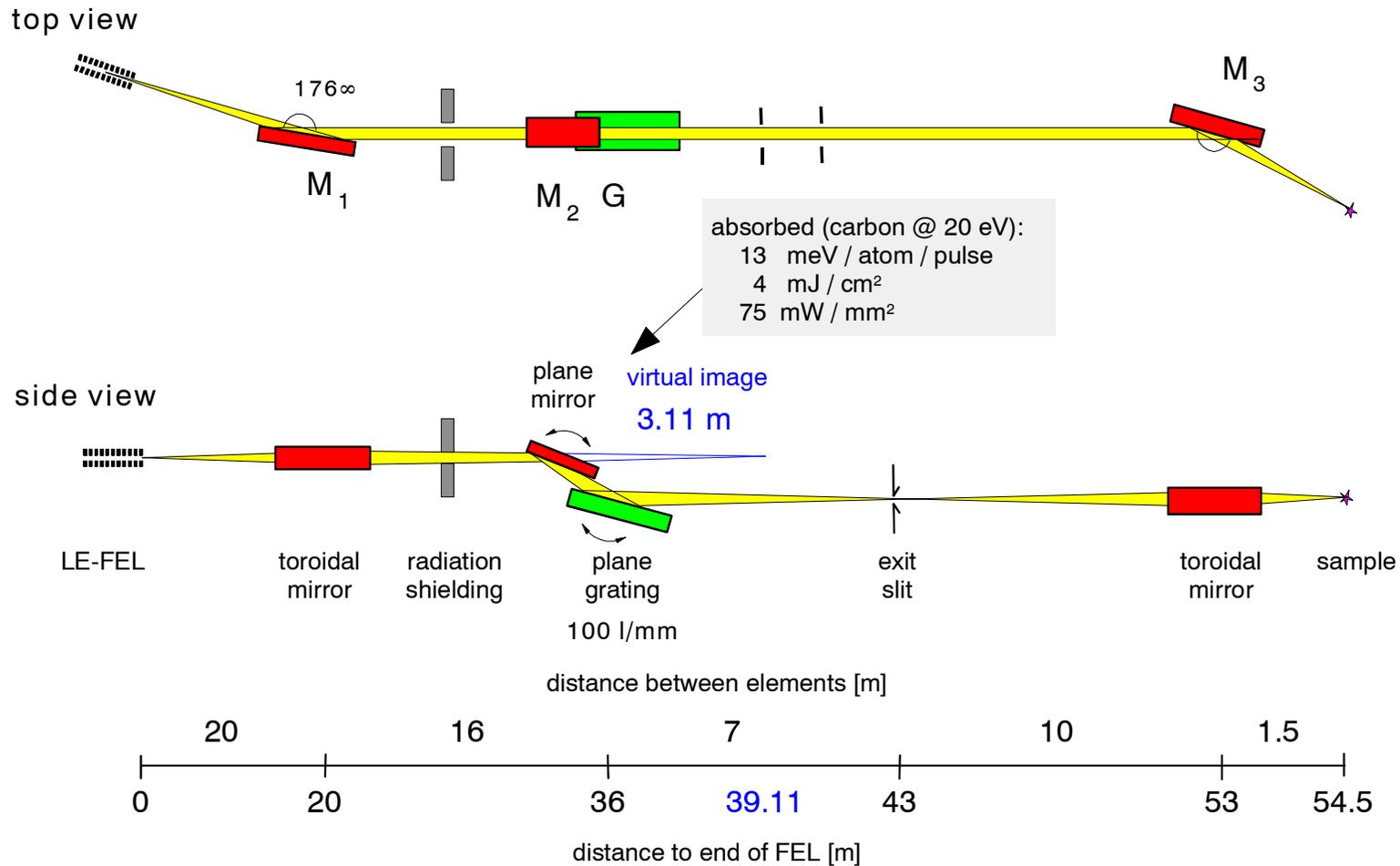
energy resolution limited by source size, large pulse length

# Low energy beamline (short pulse)

optical design

PGM in convergent light

$c=1.5, 20-250 \text{ eV}$

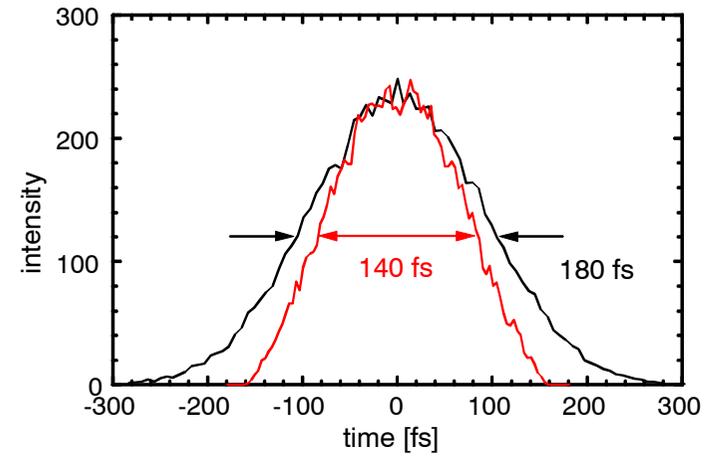
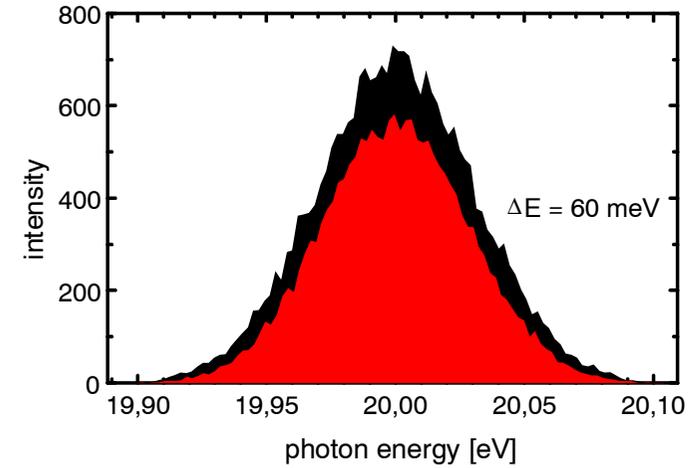
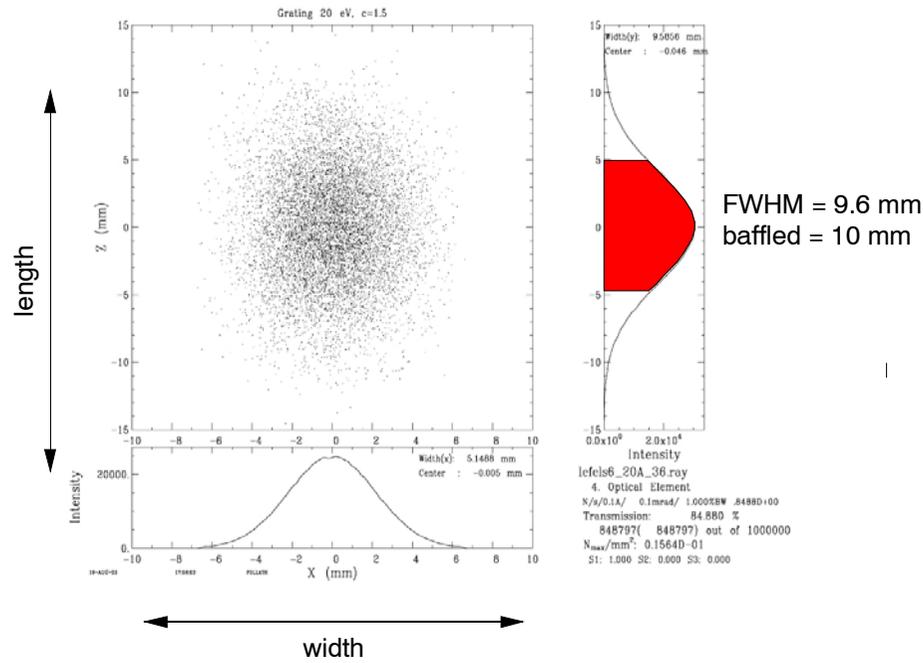


# Low energy beamline (short pulse)

# pulse broadening

20 eV, 100 l/mm, c=1.5, 200 μm slit

grating illumination



	source	focus
pulse length [fs]	120	180 / 140
bandwidth [meV]	160	60 / 60

pulse length preserved, resolution bad

- first beamlines designed
- optical elements survive intense FEL - beam irradiation
- dedicated beamline for pulse length conservation (100 fs)
- high resolution possible (30.000)
- performance benefits from improved FEL-source properties